
ANIMAL RESEARCH PAPER

Dietary options to reduce the environmental impact of milk production

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SUMMARY

A range of options was explored to test the hypothesis that diets for dairy cows could be formulated to reduce the carbon footprint (CFP) of feed, increase efficiency of conversion of potentially human-edible feed into milk, increase nitrogen use efficiency (NUE) and reduce methane (CH₄) emissions per kg milk. Diets based on grazed grass, grass silage, maize silage or straw, supplemented with raw material feeds, were formulated to meet requirements for metabolizable energy and metabolizable protein for a range of daily milk yields. At similar levels of milk yield, NUE, predicted CH₄ emissions and diet CFP were generally higher for diets based on maize silage than for those based on grazed grass, grass silage or straw. Predicted CH₄ emissions and human-edible proportion decreased, while NUE increased with the increasing level of milk yield. It is concluded that there is potential to reduce the environmental impact of milk production by altering diet formulation, but the extent to which this might occur is likely to depend on availability of raw material feeds with low CFPs.

INTRODUCTION

The feeding of dairy cows involves formulating and delivering diets to meet nutritional requirements for specified levels of daily milk output in relation to stage of lactation, availability and cost of raw materials, and season of year. The environmental impact of milk production systems has to date received relatively little attention from legislators in Europe, except for inclusion in general restrictions on manure and waste disposal. In contrast, there has been legislation in the USA since 2003 to control the environmental impact of concentrated animal feeding operations (CAFO) where the main emphasis is on control of point-source pollution of water-courses. Current CAFO regulations include dairy units of 200 cows or more where the animals are housed for more than 45 days per annum and where crops are not grown on the unit (US Environmental Protection Agency 2012). European pig and poultry systems are controlled under the European Union Integrated Pollution Prevention and Control (IPPC)

Directive 2010/75/EU, which requires agricultural activities with a high pollution potential to have a permit (Anonymous 2015). The emphasis is on controlling pollution of water by components of manure (such as nitrates and phosphates) and pollution of air, mainly by ammonia. Dairy units are not included in the current IPPC regulations (Eurostat 2013), but the situation is under review.

Concern over rising concentrations of greenhouse gases (GHG) in the atmosphere led to publication by the United Nations Food and Agriculture Organisation (FAO) of 'Livestock's Long Shadow' (Steinfeld *et al.* 2006), which drew attention internationally to the environmental impact of livestock production. In 2008, the UK Government published the Climate Change Act (Office of Public Sector Information 2014), which set ambitious targets for reduction of GHG emissions, including those from agriculture. The FAO published subsequently a more detailed life-cycle assessment of GHG from the dairy sector (Gerber *et al.* 2010) and a detailed assessment of global ruminant supply chains (Opio *et al.* 2013). These reports highlighted the significance of enteric emissions of methane (CH₄) from dairy cattle together

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with emissions of carbon dioxide (CO₂) and nitrous oxide (N₂O) from feed production and of N₂O and CH₄ from manure and manure management systems. Global cattle emissions were estimated to amount to 4256 Mt CO₂ equivalents (CO₂e), of which 1419 Mt were from milk production and 2837 Mt from beef production. Average emission intensity was 2.8 kg CO₂e/kg fat and protein-corrected milk. However, there was a large range in emission intensity between regions and systems of production, with arid regions having the highest emission intensity, humid regions intermediate and temperate regions the lowest (Opio *et al.* 2013).

Average emission intensity for temperate milk production was 1.9 kg CO₂e/kg product for grassland systems and 1.6 kg CO₂e/kg product for mixed systems, with relatively little difference between temperate grassland and mixed systems in proportions of emissions from enteric fermentation, manure and fertilizer, feed and energy use. Overall, enteric CH₄ accounted for 0.47 of total dairy emissions, feed production and processing (including fertilizer, crop residues and land use change) accounted for 0.24 of total emissions, and manure (including manure management systems) accounted for 0.26 of total emissions (Opio *et al.* 2013).

Another important consideration for livestock production is competition for arable land to grow crops for human food *v.* animal feed. This will be central to global food security in the future because arable land is limited. Ruminant production potentially has a distinct advantage over pig and poultry production because ruminants can utilize grazed grass, forage and co-products that are unsuitable for human consumption, whereas pigs and poultry compete directly with humans for the majority of their dietary ingredients (Wilkinson 2011).

The objective of the work reported in the present paper was to test the hypothesis that diets for dairy cows could be formulated to reduce the total diet carbon footprint (CFP) and also reduce the proportion of human-edible feed in the total diet. Effects on feed nitrogen use efficiency (NUE) and enteric CH₄ emissions per kilogram milk of implementing a range of nutritional strategies were also explored for cows differing in daily milk yield specified in diet formulation. The dietary strategies considered here are relevant to conventional systems of milk production operated on farms in Northern Europe and America. Organic options have been explored elsewhere (e.g. Olesen *et al.* 2006; Williams *et al.* 2006; Weiske & Michel

2007), as have feed supplements and feeding management in terms of their potential to reduce greenhouse gas emissions and increase efficiency of animal performance (e.g. Blaxter & Czerkawski 1966; Tamminga *et al.* 2007; Bodas *et al.* 2008; Hristov *et al.* 2013; White & Capper 2014).

MATERIALS AND METHODS

Diets were formulated using the Ultramix diet formulation programme (AGM Systems Ltd., Romsey, UK). Ultramix incorporates a database containing the composition of feed raw materials, a modelling package containing equations to calculate nutrient requirements, a linear programming package to calculate least-cost formulations and a report-writing module to present results. Equations of the Feed into Milk (FiM) feeding system for dairy cows (Thomas 2004) were used in the modelling package to calculate maximum dry matter (DM) intake (DMI), metabolizable energy (ME) and metabolizable protein (MP) requirements and supply, extended to calculate nitrogen (N) excretion. Factors affecting predicted CH₄ emissions were also considered, together with interactions between CH₄ and N emissions. The CFP of each diet was calculated and the effect on diet CFP of varying raw material feed ingredients was explored. Point feed conversion efficiencies, *i.e.* not including the rearing or dry periods, defined as kg milk yield per kg DMI were explored together with the effect of diet formulation on the proportion of potentially human-edible DM in the total diet DM.

Diet specifications

Across all diets the following animal specifications were kept constant: Live weight = 650 kg; milk fat concentration = 39 g/kg; milk protein concentration = 31 g/kg. Diets were formulated at three levels of milk yield: 20, 30 and 40 kg/d, for which maximum live-weight changes were 0, -0.5 and -0.6 kg/d, respectively. These levels of milk yield and live-weight change were chosen to represent the range of formulation targets that might be encountered on dairy farms.

A maximum constraint was imposed for DMI and minimum constraints were imposed for ME and MP requirements. To ensure that N supply did not limit microbial protein synthesis, the ratio of effective rumen degradable protein (ERDP) to microbial crude protein (MCP) was constrained to a minimum of 1.0.

To minimize the risk of acidosis, and to encourage rumination and butterfat synthesis, rumen stability value (RSV) balance (Thomas 2004) was constrained to a minimum of +20 and the proportion of total DMI derived from forage DM was constrained to a minimum of 0.4.

Intake of forage was not constrained. Maximum intake of individual non-forage raw materials was constrained to 4 kg/d, except sugar beet pulp, which was constrained to a maximum of 6 kg/d, and protected fat, which was constrained to a maximum of 0.6 kg/d. Diets were not formulated for mineral and vitamin requirements; a fixed quantity of mineral and vitamin supplement was included at 0.2 kg/d.

Feeds

A database of feeds was constructed from raw materials in common use in diets for dairy cows, i.e. grazed grass, grass and maize silages, cereal grains, oilseeds, co-products and rumen-protected fat (Appendix 1). In addition, a set of diets was formulated with chopped wheat straw as the only forage, and some additional co-product feeds (i.e. biscuit meal, breakfast cereal and moist distillers' grains) to emulate the experimental diet used by Roberts & March (2013).

Values for the CFP of diet ingredients were obtained from the Dutch FeedPrint database (Vellinga *et al.* 2012; Appendix 1). Diet CFP was calculated as the sum of CFPs of individual ingredients. Each ingredient CFP included CO₂e released during crop growth (e.g. seed, pesticides, green manure, crop residues, organic manure, fertilizer, fuel for cultivation), storing the crop (including crop losses during storage), transporting the crop (to processing, feed mill and farm) and processing the crop (e.g. drying, grinding). Each ingredient CFP also included allowances for land use (changes in management) allocated on the basis of long-term equilibrium (e.g. 200 years for permanent grassland) and land-use change (e.g. deforestation) allocated on a global basis, so as not to penalize unduly individual crops or land that has been in cultivation for many years. Values for the CFP of raw materials used in the diets (with the exception of grazed grass and grass silage) were Dutch averages that allowed for potentially different CFP of imported and home-grown commodities according to the balance of trade and countries of origin. For co-products, such as soya bean meal and sugar beet pulp, CFP components were allocated within FeedPrint to primary and secondary products on the basis of economic value.

To provide a metric to evaluate competition for land use between human food and animal feed, Wilkinson (2011) allocated proportional values to different categories of raw materials according to their estimated potential use for human food. Grass and forages were allocated a value of zero; cereals, pulses and soya bean products were allocated a value of 0.8; other oilseeds, cereal and food co-products, such as sugar beet pulp, were allocated a value of 0.2. Thus, a potential human-edible proportion was calculated for each ingredient and for the formulated diets.

Nitrogen supply and utilization

In the FiM system (Thomas 2004), MP supply is calculated from flows of digestible microbial true protein and digestible undegradable protein at the small intestine. Requirements for MP are calculated from milk protein yield, pregnancy, live-weight change and endogenous N losses in urine, faeces, hair and scurf. By definition, protein that is not digested or metabolized is excreted in faeces or urine. Nitrogen excretion was, therefore, calculated from the FiM equations by summing the indigestible and non-metabolizable fractions at each step (Fig. 1 and Appendix 2). Urinary N losses included endogenous urinary protein, excess ERDP, microbial non-protein N, and the difference between net protein and MP required for milk protein synthesis. An adjustment was made for the non-protein N (urea) content of milk to allow for this alternative route of N excretion. Faecal N losses included endogenous faecal protein, acid-detergent insoluble N, indigestible undegradable protein, and indigestible microbial true protein. An adjustment was made for endogenous protein absorbed from the hind-gut, as indicated in FiM. Nitrogen excretion was the sum of urinary and faecal N losses. Nitrogen use efficiency was calculated as total N output in milk protein divided by total N intake.

Methane emissions

Methane emissions were calculated from the composition and predicted intake of the formulated diets using the equation of Yates *et al.* (2000):

Methane output (MJ/day)

$$= 1.36 + 1.21 \text{ DMI} - 0.825 \text{ CDMI} + 12.8 \text{ NDF}$$

where CDMI is concentrate intake (kg DM/day) and NDF is neutral detergent fibre concentration (kg/kg total diet DM).

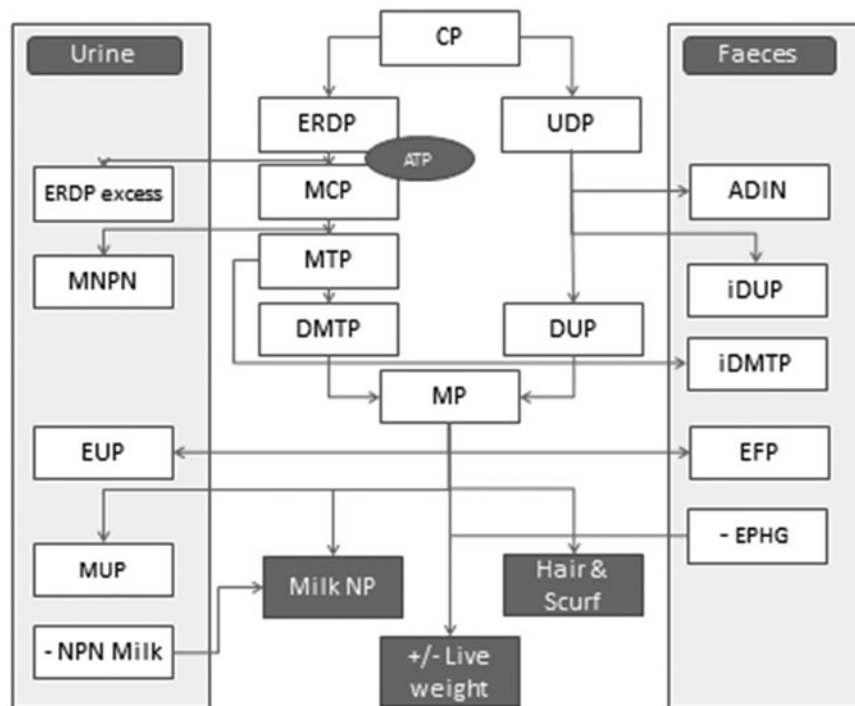


Fig. 1. Flow of nitrogen from dietary crude protein intake to fractions in urine, faeces, milk and body tissue. For abbreviations see Appendix 2.

Feed conversion efficiency

An indirect indicator of GHG emissions is feed conversion efficiency (FCE), defined conventionally as average daily output of energy-corrected milk per annum divided by average daily total DMI. Feed conversion efficiency is inversely related to CH₄ per unit of milk output (Colman *et al.* 2011) and varies widely between dairy systems in different regions of the world, reflecting the wide range in diet quality (FAO, IDF & IFCN 2014). In the present study, point FCE (pFCE) values were calculated to allow comparisons between levels of milk yield and between diets. Values for pFCE are higher than typical values for FCE in the literature because they are calculated from output and input on a single day in lactation rather than as annual averages, which include the dry period when feed is consumed but milk yield is zero.

Diet formulations

For each daily milk yield level (20, 30 or 40 kg/d per cow), diets were formulated to represent a range of contrasting forage-feeding systems: (i) grazed grass, (ii) grass silage, (iii) maize silage and (iv) straw.

To test the scope for lowering diet CFP, the diet based on maize silage at a milk yield level of 40 kg/day was

taken as a baseline diet (Base) and diet CFP was imposed as a constraint with progressively lower values until no feasible solution could be found to the formulation. The feasible diet with the lowest possible CFP was designated Low-C. Another diet was formulated (Low-C2) in which proportions of forages were constrained to the same as the baseline diet, but sources and proportions of other raw materials could vary with decreasing CFP, thereby testing the scope for lowering CFP of diets by adjusting only ingredients of concentrates.

RESULTS

Grazed grass

Diet formulations for grazed grass are shown in Table 1 for each level of daily milk yield. For all three milk yield levels, DMI and ME requirement were active nutrient constraints; for milk yields of 30 and 40 kg/day, MP requirement was also an active nutrient constraint; ERDP to MCP ratio and RSV were not active constraints in grazed grass diets. There was little difference between diets formulated for milk yields of 20 and 30 kg/day, but when level of milk output was increased from 30 to 40 kg/day, greater quantities of concentrate supplements were required to meet total ME requirement. Nitrogen

Table 1. Diet formulations based on grazed grass, grass silage, maize and grass silage, and straw for milk yields of 20, 30 and 40 kg/day

Milk yield (kg/day)	Grazed grass			Grass silage			Maize/grass silage			Straw		
	20	30	40	20	30	40	20	30	40	20	30	40
<i>Raw materials (kg DM/day)</i>												
Grazed grass	10.2	11.7	10.8									
Grass silage				11.3	9.2	10.9	2.7	3.3	4.0			
Maize silage							8.2	10.1	11.9			
Wheat straw										5.2	5.2	5.6
Wheat		0.7	3.5		2.3	2.0						
Barley	3.4	3.4	3.4	3.4	3.4	3.4	3.4	2.1	3.4			
Sugarbeet pulp	0.8			1.2	3.1	1.9				1.7	3.9	5.3
Wheatfeed							0.9	3.4				
Breakfast cereal										2.9	3.0	3.1
Biscuit meal										3.6	3.6	1.8
Moist distillers' grains										1.3	1.2	2.7
Soya bean meal		0.3	1.7		0.5	2.8			1.0			1.5
Rapeseed meal									1.9	1.4	2.4	
Wheat DDGS												2.9
Urea							0.2	0.2				
Bypass fat		0.5	0.6			0.6			0.4			
Minerals	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
TOTAL	14.6	16.8	20.2	16.1	18.6	21.7	15.5	19.2	22.6	16.2	19.5	23.1
pFCE	1.38	1.79	1.98	1.24	1.61	1.88	1.29	1.56	1.80	1.21	1.51	1.86

DM, dry matter; DDGS, Distillers' dried grains with solubles; pFCE, Point Feed Conversion Efficiency (kg milk/kg DM intake).

excretion and NUE increased with increasing milk yield, but N excretion decreased when expressed per unit of milk yield (Fig. 2). Predicted CH₄ emissions per kg of milk decreased with increasing milk yield (Fig. 3). Diet CFP per kg of milk showed little change with level of milk yield, reflecting substitution of grazed grass with feeds of higher CFP at higher levels of milk yield. Proportion of human-edible raw materials increased with increasing milk yield level (Fig. 3), reflecting higher levels of cereal grain in diets.

Grass silage

Formulations for diets based on grass silage are presented in Table 1. As with diets based on grazed grass, quantities of raw materials in each diet depended on raw materials offered, raw material composition and constraints imposed. For all three milk yield levels, DMI and ME requirement were active nutrient constraints; for milk yields of 30 and 40 kg/day, MP requirement was also an active nutrient constraint; for a milk yield of 30 kg/day, ERDP to MCP ratio was an active constraint; for a milk yield of 40 kg/day, RSV was an active constraint. Total N

excretion (g/day) increased with increasing milk yield (Fig. 2). As with the diets based on grazed pasture, predicted CH₄ emissions per kg of milk decreased with increasing milk yield. However, diet CFP per kg of milk produced varied little with milk yield (Fig. 3).

Maize silage

Diets based on maize silage are also shown in Table 1. For all three milk yield levels, DMI and ME requirement were active nutrient constraints; for milk yields of 30 and 40 kg/day, MP requirement was also an active nutrient constraint; for all three milk yield levels, ERDP to MCP ratio was an active constraint. Total N excretion increased with increasing level of milk yield, but decreased per unit of product with increasing level of milk yield. Nitrogen use efficiency increased with increasing level of milk yield (Fig. 2). As with the diets based on grass silage, predicted CH₄ emissions per unit of product decreased with increasing level of milk output (Fig. 3).

Straw

The final columns of Table 1 show diets formulated with chopped wheat straw and a range of co-product

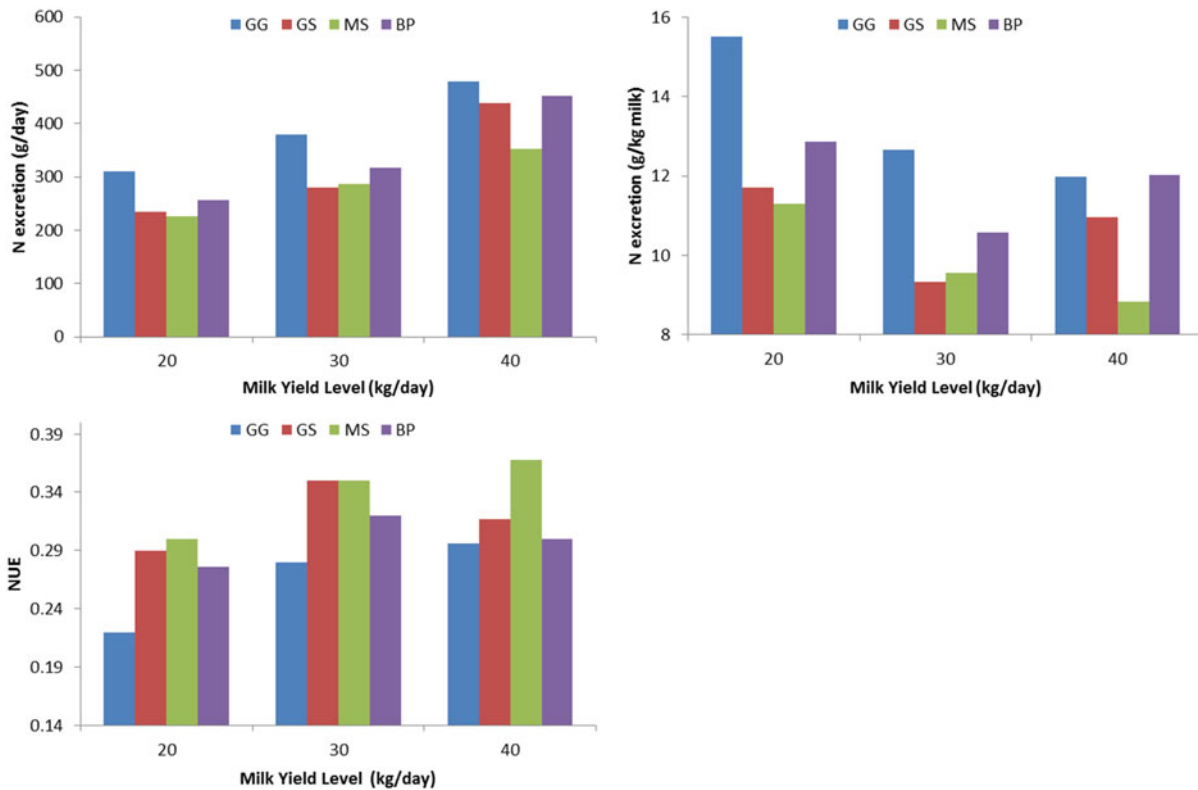


Fig. 2. Nitrogen excretion and efficiency (NUE) for diets formulated from grazed grass (GG), grass silage (GS), maize and grass silages (MS) and co-products (BP). (Colour online).

feeds. For all three milk yield levels, DMI, ME requirement and MP requirement were active nutrient constraints; for milk yields of 20 and 30 kg/day, ERDP to MCP ratio was an active constraint; RSV was not an active constraint in straw-based diets. Straw contributed 0.32 of total diet DM for 20 kg milk/day, 0.26 of total diet DM for 30 kg milk/day and 0.24 of total diet DM for 40 kg milk/day. Total N excretion (g/day) increased with level of milk output, but there was no consistent trend in N excretion per unit of product or in NUE (Fig. 2). Predicted CH₄ emissions decreased with increasing level of milk yield, but diet CFP per unit of milk was similar for the three levels of milk yield (Fig. 3). The human-edible proportion was low for all levels of milk output, reflecting the relatively large contribution of co-product feeds to the total diet.

Diets with low carbon footprint

The diet with the lowest CFP (Low-C; Table 2) had a diet CFP that was 40% lower than that of the baseline diet and contained maize silage together with a high proportion of co-product feeds with low CFP. Active nutrient constraints for this diet were DMI, MP

requirement, ERDP to MCP ratio and RSV; ME requirement was no longer an active constraint, so ME was oversupplied by 21 MJ/d (0.08 of ME requirement).

The diet with the lowest CFP formulated by changing concentrate ingredients (Low-C2; Table 2) had a diet CFP 30% lower than that of the baseline diet and relied on raw materials with high nutrient density (e.g. soya bean meal) to achieve the reduction in diet CFP. Active nutrient constraints for this diet were DMI, MP requirement, and ERDP to MCP ratio; ME requirement was no longer an active constraint, but ME was oversupplied by only 1 MJ/d.

DISCUSSION

Nitrogen use efficiency

Comparison of the diets based on grazed grass, grass silage or maize silage revealed that the lowest levels of N excretion and the highest NUE were obtained with the diets based on maize silage, in agreement with Tamminga *et al.* (2007) and Reynolds *et al.* (2010). This is because maize silage has a relatively low concentration of N, and the N in maize silage is less degradable than N in grass and grass silage.

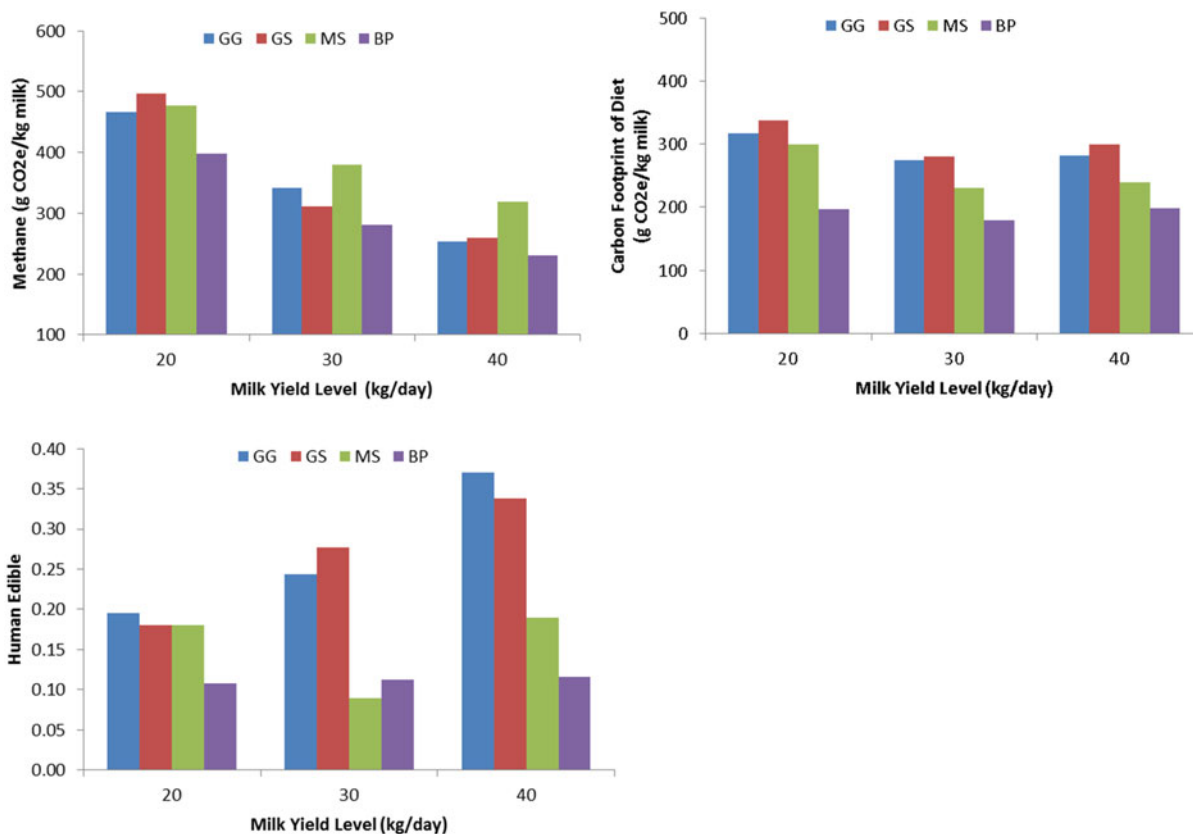


Fig. 3. Predicted methane emissions, diet carbon footprint and human-edible proportion for diets formulated from grazed grass (GG), grass silage (GS), maize and grass silages (MS) and co-products (BP). (Colour online).

Consequently, diets based on maize silage were associated with a better match between ERDP supply and ERDP requirement. In the present study, urea was included in the maize-silage diets for milk yields of 20 and 30 kg/d, so ERDP requirement was met exactly. Diets based on grass silage had lower N excretion and greater NUE than diets based on grazed grass. This can be attributed to the higher N content of grazed grass, which consists of more leafy material harvested at an earlier stage of growth than ensiled grass. Although rumen degradability of N can vary with different silage additives, total N concentration of grass silage is usually similar to total N concentration of the fresh grass from which it is made (Grenet 1983). The main environmental consequence of grazing pasture of high N concentration is low NUE (<0.20 for some pasture-based systems with high inputs of artificial fertilizer N) because NUE is inversely related to total N intake (Dewhurst 2006; Ledgard *et al.* 2009). In view of the importance of grazed grass in milk production systems (Gerber *et al.* 2010; Opio *et al.* 2013), the significant contribution of fertilizer N, manure N and grazing returns of N

to N₂O emissions from soils under grassland (Opio *et al.* 2013), and the relatively high concentration of CP in grazed grass, ways of increasing NUE of grazing dairy cows as a potential GHG mitigation strategy are essential. For intensive grazing systems, high-sugar grasses potentially offer a better balance between ERDP and fermentable carbohydrates within the grass, resulting in greater NUE (Miller *et al.* 2001). Alternatively, as with any diet that supplies excess ERDP, supplementation with fermentable carbohydrates is an effective strategy to increase capture of excess ERDP and increase MCP generation; this strategy is more effective at increasing NUE than altering the CP of the overall diet (Broderick 2003; Sinclair *et al.* 2014).

Diets based on straw and co-products were included in the present study to explore the potential for formulation of diets that do not require any land for primary production of animal feeds. These unusual diets were based on an experimental diet in use at a UK research centre where cows yielded in excess of 10 500 kg milk in the 12 months to April 2013 (Roberts & March 2013). Across all milk yield

Table 2. Diets formulated to give the lowest feasible diet carbon footprint (CFP, milk yield 40 kg/day)

	Base (Table 1)	Low CFP whole diet (Low-C)	Low CFP concentrate only (Low-C2)
Raw materials (kg DM/day)			
Maize silage	11.9	14.3	11.9
Grass silage	4.0		4.0
Moist distillers' grains		3.1	1.3
Barley	3.4		
Sugarbeet pulp		1.1	
Breakfast cereal		3.8	3.8
Soya bean meal	1.0	1.0	1.6
Rapeseed meal	1.9		
Bypass fat	0.4		
Minerals	0.2	0.2	0.2
Diet CFP (g CO ₂ e/kg milk)	239	142	168
NUE	0.37	0.35	0.37
Human-edible DM in total diet DM	0.19	0.16	0.09

DM, dry matter; NUE, nitrogen use efficiency.

levels, NUE for straw-based diets was intermediate between NUE for grass- and silage-based diets. The low ME and CP concentrations of straw resulted in much lower proportions of forage in straw-based diets (0.24–0.31 of total DM) than in silage-based diets (0.53–0.70 of total DM), so NUE depended more on composition of supplementary co-products offered rather than the basal forage.

In general, NUE increased with increasing levels of milk yield. This was to be expected because as milk yield increased the protein required for maintenance, i.e. non-productive protein, became a decreasing proportion of total protein requirement. Also, as milk yield increased the proportion of forage in diets tended to decrease as more constraints became active in formulations, and the selected supplementary ingredients tended to have higher energy to protein ratios in order to meet increased energy requirements. In typical diet formulation scenarios, energy is the most expensive constraint, so at lower levels of production least-cost solutions will over-supply protein. Another factor that affects the relationship between NUE and milk yield in the present study is live-weight loss. Live-weight loss was set at zero for milk yield of 20 kg/d, 0.5 kg/d for milk yield of 30 kg/d and 0.6 kg/d for milk yield of 40 kg/d. These are typical allowances encountered in practice, but live-weight loss inflates NUE when calculated on a daily basis because the dietary N originally used to generate the protein reserves is not taken into account. Live-weight loss provides the equivalent of 138 g MP per kg loss

(Thomas 2004) which, in the present study, corresponds to 0.035 of daily MP requirement for milk yields of 30 and 40 kg/d. Adjusting to zero live-weight loss for milk yields of 30 and 40 kg/d reduces mean NUE from 0.33 to 0.32, but does not alter the underlying principle that NUE is positively related to milk yield.

The present study was designed to explore dietary options for reducing environmental impact of dairy systems. The boundaries of the analysis, therefore, are from feeds consumed to release of potential pollutants by the cow. Additional options are available to improve NUE of the whole farm, including crop husbandry and manure management, but these are beyond the scope of the present study. Proportions of N lost after excretion can vary between 0.01 and 0.99 of N excreted, depending on housing, manure handling and storage methods (Rotz 2004). The less N excreted, however, the less is available to cause emissions of N₂O, since under the Tier 1 methodology of the Intergovernmental Panel on Climate Change (IPCC) the emission factor for N₂O is a fixed proportion (0.01) of total N applied (De Klein *et al.* 2006).

Methane emissions

Predicted CH₄ emissions per kg of milk decreased with increasing milk yield, as observed on commercial farms (Garnsworthy *et al.* 2012a, b; Bell *et al.* 2014). Many studies have shown that maize silage reduces CH₄ emissions compared with grass silage (e.g. Tamminga *et al.* 2007; Garnsworthy *et al.* 2012a),

although mitigation of CH₄ emissions may be offset by soil carbon loss following the ploughing of grassland for maize cultivation (Vellinga & Hoving 2011). Methane emissions are related positively to dietary NDF concentration and inversely related to concentrate proportion (Yates *et al.* 2000), so predicted CH₄ per litre of milk decreased as mean NDF decreased from 431 to 358 g/kg DM, and mean proportion of concentrates increased from 0.30 to 0.35 of total DMI when comparing grazed grass and maize silage. Substitution of grass silage by legume silage may reduce CH₄ emissions per unit of silage DM consumed (Waghorn *et al.* 2002; Kasuya & Takahashi 2010), but it is not known if the reduction in methanogenesis would be evident in the mixed diets simulated in the present study. Other methods of predicting CH₄ production may give different results; for example, those described in Gibbs *et al.* (2002) and Dong *et al.* (2006) do not take account of differences in diet composition other than its overall effect on digestibility and/or gross energy intake.

Human edible feed use

Human-edible feeds may potentially be consumed by the human population (e.g. cereal grains, pulse grains, soya bean meal) whereas inedible feeds (e.g. rapeseed meal, distillers' dried grains with solubles) cannot. Wilkinson (2011) and Ertl *et al.* (2015) discussed the basis of allocation of feeds and their respective human-edible proportions. The application of the concept of human-edible and inedible feeds to feed efficiency was considered by a task force of the Council for Agricultural Science and Technology (CAST 1999). The task force concluded that measures of efficiency of whole-diet feed use did not take into account the considerable proportion of inedible feeds in ruminant rations. The concept was taken further by Wilkinson (2011) and Ertl *et al.* (2015), who concluded that milk could make a net contribution to human food supply since more human-edible energy and protein was produced in milk than was consumed by cows in feed.

Ertl *et al.* (2015) found that human-edible feed efficiency (kg milk/kg feed) at the whole-farm scale was negatively correlated with amount of concentrates per kg milk and positively correlated with the area of grassland utilized per tonne of milk produced. In contrast, in the present study where diet formulation was altered within constraints of animal requirements to meet specified levels of daily milk yield, the highest

human-edible proportions at each level of daily milk yield were in the diets based on grazed grass and grass silage, reflecting the need to supplement these forages with cereal grain to meet ME requirements and, at the two higher levels of milk yield, soya bean meal to meet MP requirements. Where the forage source was maize silage, the human-edible proportion of the diet was reduced compared with the diets based on grazed grass and grass silage due to reduced input of supplementary cereal grain, and was reduced further in the diets based on straw and co-products that contained no cereal grain.

Feed conversion efficiency

The main factor influencing pFCE was level of milk yield. Mean pFCE (kg milk/kg DMI) were 1.3 at 20 kg milk/day, 1.6 at 30 kg and 1.9 at 40 kg milk/day; pFCE increased by 0.03 kg/kg, or 3.4 kg milk, per 0.1 FCE unit. Estimated global average response, including feed consumed in the dry period, was 2.5 kg milk per 0.1 unit increase in FCE (FAO, IDF & IFCN 2014). Differences between forage sources in pFCE were generally small at the same milk yield, reflecting similar total daily DMI and diet formulations that balanced variations in forage quality with concentrates to meet requirements for ME within DMI constraints. Across the range in levels of milk yield, pFCE values tended to be highest for diets based on grazed grass (1.7 kg milk/kg DMI) and lowest for straw-based diets (1.5 kg/kg) with diets based on silage being intermediate (1.6 kg/kg).

Feed carbon footprint

Globally, emissions from dairy feed production and processing, account for about 0.2 of the total CFP of milk production systems (Opio *et al.* 2013). O'Brien *et al.* (2014) estimated that purchased concentrate feeds accounted for 0.12 of total emissions in a housed mixed forage/concentrate system of milk production in which diets were similar to those based on maize silage in the present study and with feed emission burdens allocated on the basis of relative economic value, as in the present study. Although O'Brien *et al.* (2014) used a range of forages and raw material feeds, they did not study the effect of changing diet formulation on diet CFP at different daily milk yields.

The allocation of emission burden on the basis of relative economic value of primary products and co-products (Vellinga *et al.* 2012) may be criticized on

the basis that the choice of relative values may be inappropriate and can change over time. Nevertheless, although co-product raw materials are important components of animal feeds (Wilkinson 2013), they are by definition produced as a consequence of the production of the primary product, usually a human food or drink, and are thus generally considered of lower economic value.

Imposing diet CFP as a constraint demonstrated that diet CFP could be reduced by up to 40% compared with the baseline diet. As expected, the diet contained maize silage together with a high proportion of co-product feeds with low CFP. However, ME was oversupplied by 8% of requirement. Oversupply of ME is unusual in least-cost diet formulations because the marginal cost for energy is usually greater than for other nutrient constraints. With CFP as the main constraint, however, raw materials with the lowest CFP are preferred, and energy is no longer the most expensive constraint. There was less scope for lowering diet CFP by altering ingredients of concentrates, but Diet Low-C2 had a diet CFP 30% lower than that of the baseline diet.

The value for the CFP of soya bean meal used in the present study was 1056 g CO₂e/kg DM, which is comprised of 625 g CO₂e/kg DM derived from growing, processing and transporting the crop, and 431 g CO₂e/kg DM derived from land use and land-use change. This CFP is considerably lower than the value used in some studies (e.g. 7690 g CO₂e/kg DM for Brazilian soya bean meal in Gerber *et al.* 2010) due to a difference in allocation of land-use change, and acknowledges that most soya bean production is on land that has been in arable cropping for more than 20 years and is now in carbon equilibrium. Soya bean production in America has lower GHG associated with its production than UK winter oilseed rape (Wilkinson & Audsley 2013). Transporting soya bean meal overseas has only a marginal effect on its CFP compared with GHG from crop production, and Lehuger *et al.* (2009) found that a dairy cow diet containing Brazilian soya bean was more environmentally efficient than one containing European rapeseed meal when land use change was excluded from the analysis. For a detailed review of land-use change in soya bean production see Opio *et al.* (2013).

In formulating the diet for the lowest feasible concentrate CFP (Diet Low C-2), soya bean meal was included at 1.6 kg DM/day, which might seem counter-intuitive given the relatively high CFP of soya bean meal (1056 g CO₂e/kg DM) compared

with alternatives such as wheat distillers' dried grains with solubles (DDGS, 797 g CO₂e/kg DM), rapeseed meal (714 g CO₂e/kg DM) and wheatfeed (359 g CO₂e/kg DM). Replacing soya bean meal by rapeseed meal, wheat DDGS and wheatfeed increased the CFP of the whole diet and decreased NUE. This is because soya bean meal has a more favourable ratio of DUP to CFP (0.18) than the other materials (mean 0.14). In other words, of the protein-rich raw materials, soya bean meal is competitive environmentally with other raw materials. The trend to more soya bean meal being produced from land that has been in arable cultivation for more than 20 years will help to sustain soya bean meal as a suitable raw material for inclusion in low CFP diets because of its high concentration of both CP and ME in addition to its superior amino acid profile.

As well as reducing diet CFP, diets Low-C and Low-C2 also had lower human-edible proportions compared with the base diet. Furthermore, the Low-C and Low-C2 diets had similar diet CFP to the diets based on straw and co-products.

A common aspiration of milk producers has been to increase annual milk output per cow. In the UK, for example, average milk yield per cow increased progressively over the period 1990–2013 (Department for Environment, Food and Rural Affairs (DEFRA) 2014). Higher milk output gave environmental gains in terms of reductions in CH₄ per litre of milk, in agreement with practice on commercial farms (DairyCo 2012; Bell *et al.* 2014), and also in terms of increased NUE. In the present study, however, there was no benefit at the highest level of milk yield in terms of lower diet CFP per kg of milk or in terms of reduced human-edible proportion, due to greater quantities of cereal grain and soya bean meal in the diet formulations. A life-cycle assessment comparing high-yielding dairy systems based on either grazing in Ireland or feeding silages in UK and USA found that unless carbon sequestration is considered significant for grassland, grass-based and continuously housed dairy systems have similar CFPs per unit of milk, but silage-based systems have greater feed and N efficiencies (O'Brien *et al.* 2014).

CONCLUSIONS

The hypothesis is accepted that diets for dairy cows can be formulated to reduce the CFP of the diet and also increase efficiency of conversion of potentially human-edible feed. However, the extent to which

the environmental impact of feed use by dairy cows may be reduced via diet formulation depends on choice and availability of raw material concentrate feeds, level of milk output and whether or not the desired environmental outcome is reduced CH₄ emissions, reduced diet CFP, increased NUE, reduced human-edible feed use, or some combination of these objectives.

Diets formulated to include high proportions of co-product feeds are capable of supporting high levels of milk output and are environmentally attractive compared with those based on grazed pasture or silage with concentrates formulated specifically for reduced diet CFP.

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REFERENCES

- Anonymous (2015). Directive 2010/75/EU integrated pollution prevention and control. *Official Journal of the European Union* **L334**, 17–119. Available from: <http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32010L0075&qid=1431954176151&from=EN> (verified 18 May 2015).
- BELL, M. J., POTTERTON, S. L., CRAIGON, J., SAUNDERS, N., WILCOX, R. H., HUNTER, M., GOODMAN, J. R. & GARNSWORTHY, P. C. (2014). Variation in enteric methane emissions among cows on commercial dairy farms. *Animal* **8**, 1540–1546.
- BLAXTER, K. L. & CZERKAWSKI, J. (1966). Modifications of the methane production of the sheep by supplementation of its diet. *Journal of the Science of Food and Agriculture* **17**, 417–421.
- BODAS, R., LOPEZ, S., FERNANDEZ, M., GARCIA-GONZALES, R., RODRIGUEZ, A. B., WALLACE, R. J. & GONZALES, J. S. (2008). *In vitro* screening of the potential of numerous plant species as antimethanogenic feed additives for ruminants. *Animal Feed Science and Technology* **145**, 245–258.
- BRODERICK, G. A. (2003). Effects of varying dietary protein and energy levels on the production of lactating dairy cows. *Journal of Dairy Science* **86**, 1370–1381.
- COLMAN, D. R., BEEVER, D. E., JOLLY, R. W. & DRACKLEY, J. K. (2011). Gaining from technology for improved dairy cow nutrition: economic, environmental, and animal health benefits. *The Professional Animal Scientist* **27**, 505–517.
- Council For Agricultural Science and Technology (CAST) (1999). *Animal Agriculture and Global Food Supply*. Task Force Report No. 135. Ames, IA, USA: CAST.
- DairyCo (2012). *Greenhouse Gas Emissions on British Dairy Farms. DairyCo Carbon Footprinting Study: Year One*. Kenilworth, UK: DairyCo. Available from: http://dairy.ahdb.org.uk/media/623464/greenhouse_gas_emissions_on_british_dairy_farms.pdf (verified 3 September 2016).
- Department For Environment, Food and Rural Affairs, DEFRA (2014). *Agricultural Statistics and Climate Change*, 5th ed. London: DEFRA. Available from: <http://www.gov.uk/government/statistics/agricultural-statistics-and-climate-change> (verified 4 June 2015).
- DE KLEIN, C., NOVOA, R. S. A., OGLE, S., SMITH, K. A., ROCHETTE, P. & WIRTH, T. C. (2006). N₂O emissions from managed soils, and CO₂ emissions from lime and urea application. In *2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4. Agriculture, Forestry and Other Land Use. Task Force on National Greenhouse Gas Inventories* (Eds S. Eggleston, L. Buendia, K. Miwa, T. Ngara & K. Tanabe), pp. 11.1–11.54. Hyama, Kanagawa, Japan: IPCC. Available from: http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_11_Ch11_N2O&CO2.pdf (verified 3 June 2015).
- DEWHURST, R. (2006). Manipulating cow diets to reduce nutrient waste to the environment. In *Proceedings of the South Island Dairy Event*. Christchurch, NZ: SIDE. Available from: <http://side.org.nz/wp-content/uploads/2014/05/4.4-Manipulating-cow-diets-to-reduce-nutrient-wastage-to-the-environment.doc> (verified 28 May 2014).
- DONG, H., MANGINO, J., MCALLISTER, T. A., HATFIELD, J. L., JOHNSON, D. E., LASSEY, K. R., DE LIMA, M. A. & ROMANOVSKAYA, A. (2006). Emissions from livestock and manure management. In *2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4. Agriculture, Forestry and Other Land Use* (Eds S. Eggleston, L. Buendia, K. Miwa, T. Ngara & K. Tanabe), pp. 10.1–10.87. Hyama, Kanagawa, Japan: IPCC. Available from: <http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html> (verified 18 November 2015).
- ERTL, P., KLOCKER, H., HÖRTENHUBER, S., KNAUS, W. & ZOLLITSCH, W. (2015). The net contribution of dairy production to human food supply: the case of Austrian dairy farms. *Agricultural Systems* **137**, 119–125.
- EUROSTAT (2013). *Agri-Environmental Indicator - Ammonia Emissions*. Luxembourg: EUROSTAT. Available from: http://ec.europa.eu/eurostat/statistics-explained/index.php/Agri-environmental_indicator_-_ammonia_emissions (verified 28 May 2014).
- FAO, IDF & IFCN (2014). *World Mapping of Animal Feeding Systems in the Dairy Sector*. Rome: FAO. Available from: <http://www.fao.org/3/a-i3913e.pdf> (verified 14 August 2014).
- GARNSWORTHY, P. C., CRAIGON, J., HERNANDEZ-MEDRANO, J. H. & SAUNDERS, N. (2012a). On-farm methane measurements during milking correlate with total methane production by individual dairy cows. *Journal of Dairy Science* **95**, 3166–3180.
- GARNSWORTHY, P. C., CRAIGON, J., HERNANDEZ-MEDRANO, J. H. & SAUNDERS, N. (2012b). Variation among individual dairy cows in methane measurements made on farm during milking. *Journal of Dairy Science* **95**, 3181–3189.

- GERBER, P., VELLINGA, T., OPIO, C., HENDERSON, B. & STEINFELD, H. (2010). *Greenhouse Gas Emissions from the Dairy Sector. A Life Cycle Assessment*. Rome: FAO.
- GIBBS, M. J., CONNEELY, D., JOHNSON, D., LASSE, K. R. & ULYATT, M. J. (2002). CH₄ Emissions from enteric fermentation. In *IPCC, Background Papers: IPCC Expert Meetings on Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (Ed. IPCC National Greenhouse Gas Inventories Programme, Technical Support Unit), pp. 297–320. Hayama, Kanagawa, Japan: IPCC. Available from: http://www.ipcc-nggip.iges.or.jp/public/gp/bgp/4_1_CH4_Enter_Fermentation.pdf (verified 18 November 2015).
- GRENET, E. (1983). Utilization of grass-silage nitrogen by growing sheep. *Journal of Agricultural Science, Cambridge* **100**, 43–62.
- HRISTOV, A. N., OH, J., LEE, C., MEINEN, R., MONTES, F., OTT, T., FIRKINS, J., ROTZ, A., DELL, C., ADESOGAN, A., YANG, W., TRICARICO, J., KEBREAB, E., WAGHORN, G., DIJKSTRA, J. & OOSTING, S. (2013). *Mitigation of Greenhouse Gas Emissions in Livestock Production – A Review of Technical Options for Non-CO₂ Emissions*. FAO Animal Production and Health paper 177. Rome: FAO. Available from: <http://www.fao.org/publications/card/en/c/87178c51-d4d1-515d-9d0e-b5a6937fa631/> (verified 26 July 2016).
- KASUYA, H. & TAKAHASHI, J. (2010). Methane emissions from dry cows fed grass or legume silages. *Asian-Australasian Journal of Animal Sciences* **23**, 563–566.
- LEDGARD, S., SCHILS, R., ERIKSON, J. & LUO, J. (2009). Environmental impacts of grazed clover/grass pastures. *Irish Journal of Agricultural and Food Research* **48**, 209–226.
- LEHUGER, S., GABRIELLE, B. & GAGNAIRE, N. (2009). Environmental impact of the substitution of soybean meal with locally-produced rapeseed meal in dairy cow feed. *Journal of Cleaner Production* **17**, 616–624.
- MILLER, L. A., MOORBY, J. M., DAVIES, D. R., HUMPHREYS, M. O., SCOLLAN, N. D., MACRAE, J. C. & THEODOROU, M. K. (2001). Increased concentration of water-soluble carbohydrate in perennial ryegrass (*Lolium perenne* L.): milk production from late-lactation dairy cows. *Grass and Forage Science* **56**, 383–394.
- O'BRIEN, D., CAPPER, J. L., GARNSWORTHY, P. C., GRAINGER, C. & SHALLOO, L. (2014). A case study of the carbon footprint of milk from high-performing confinement and grass-based dairy farms. *Journal of Dairy Science* **97**, 1835–1851.
- Office Of Public Sector Information (2014). *Climate Change Act 2008. Chapter 27*. London: HMSO. Available from: <http://www.legislation.gov.uk/ukpga/2008/27/contents> (verified 15 August 2014).
- OLESEN, J. E., SCHELDE, K., WEISKE, A., WEISBJERG, M. R., ASMAN, W. A. H. & DJURHUUS, J. (2006). Modelling greenhouse gas emissions from European conventional and organic dairy farms. *Agriculture, Ecosystems and Environment* **112**, 207–220.
- OPIO, C., GERBER, P., MOTTET, A., FALCUCCI, A., TEMPIO, G., MACLEOD, M., VELLINGA, T., HENDERSON, B. & STEINFELD, H. (2013). *Greenhouse Gas Emissions from Ruminant Supply Chains – A global Life Cycle Assessment*. Rome: FAO.
- Premier Nutrition (2014). *Premier Atlas 2014 Ingredients Matrix*. Rugeley, UK: Premier Nutrition. Available from: http://www.premiernutrition.co.uk/default.aspx?SectionID=UK_TecAt (verified 3 September 2016).
- REYNOLDS, C. K., CROMPTON, L. A., MILLS, J. A. N., HUMPHRIES, D. J., KIRTON, P., RELLING, A. E., MISSELBROOK, T. H., CHADWICK, D. R. & GIVENS, D. I. (2010). Effects of diet protein level and forage source on energy and nitrogen balance and methane and nitrogen excretion in lactating dairy cows. In *Proceedings of the 3rd International Symposium on Energy and Protein Metabolism* (Ed. G. M. Corvetto), pp. 463–464. EAAP Publication No. 127. Wageningen, The Netherlands: Wageningen Academic Publishers.
- ROBERTS, D. J. & MARCH, M. (2013). Feeding systems for dairy cows: Homegrown versus co-product feeds. In *Recent Advances in Animal Nutrition 2013* (Eds P. C. Garnsworthy & J. Wiseman), pp. 61–69. Packington, UK: Context Products Ltd.
- ROTZ, C. A. (2004). Management to reduce nitrogen losses in animal production. *Journal of Animal Science* **82**(E. Suppl.), E119–E137.
- SINCLAIR, K. D., GARNSWORTHY, P. C., MANN, G. E. & SINCLAIR, L. A. (2014). Reducing dietary protein in dairy cow diets: implications for nitrogen utilization, milk production, welfare and fertility. *Animal* **8**, 262–274.
- STEINFELD, H., GERBER, P., WASSENAAR, T., CASTEL, V., ROSALES, M. & DE HAAN, C. (2006). *Livestock's Long Shadow: Environmental Issues and Options*. Rome: FAO.
- TAMMINGA, S., BANNINK, A., DIJKSTRA, J. & ZOM, R. (2007). *Feeding Strategies to Reduce Methane Loss in Cattle*. Report 34, Animal Sciences Group, Wageningen, The Netherlands: Wageningen UR.
- THOMAS, C. (Ed.) (2004). *Feed into Milk: A New Applied Feeding System for Dairy Cows*. Nottingham, UK: Nottingham University Press.
- US Environmental Protection Agency (2012). *National Pollutant Discharge Elimination System, Compiled CAFO Final Rule Part 122 – EPA Administered Permit Programs: The National Pollutant Discharge Elimination System*. Washington, DC, USA: US Environmental Protection Agency. Available from: https://www.epa.gov/sites/production/files/2015-08/documents/cafo_final_rule2008_comp.pdf (verified 3 September 2016).
- VELLINGA, T. V. & HOVING, I. E. (2011). Maize silage for dairy cows: mitigation of methane emissions can be offset by land use change. *Nutrient Cycling in Ecosystems* **89**, 413–426.
- VELLINGA, T. V., BLONK, H., MARINUSSEN, M., VAN ZEIST, W. J. & STARMANS, D. A. J. (2012). *Methodology used in Feedprint: a Tool Quantifying Greenhouse Gas Emissions of Feed Production and Utilization*. Lelystad, The Netherlands: Wageningen UR Livestock Research.
- WAGHORN, G. C., TAVENDALE, M. H. & WOODFIELD, D. R. (2002). Methanogenesis from forages fed to sheep. *Proceedings of the New Zealand Grassland Association* **64**, 167–171.
- WEISKE, A. & MICHEL, J. (2007). *Greenhouse Gas Emissions and Mitigation Costs of Selected Mitigation Measures in Agricultural Production*. MEACAP WP3 D15a. Sixth

- Framework Programme Priority 8: Policy-Oriented Research. Specific Targeted Research Project n°SSPE-CT-2004-503604: Impact of Environmental Agreements on the CAP. London, UK: Institute for European Environmental Policy. Available from: http://www.ieep.eu/assets/613/WP3_D15_ghg_mitigation_costs.pdf (verified 3 September 2016).
- WHITE, R. R. & CAPPER, J. L. (2014). Precision diet formulation to improve performance and profitability across various climates: modeling the implications of increasing the formulation frequency of dairy cattle diets. *Journal of Dairy Science* **97**, 1563–1577.
- WILKINSON, J. M. (2011). Re-defining efficiency of feed use by livestock. *Animal* **5**, 1014–1022.
- WILKINSON, J. M. (2013). A review of changes in the use of raw materials in the manufacture of animal feeds in Great Britain from 1976 to 2011. *World Agriculture* **4**, 10–17.
- WILKINSON, J. M. & AUDSLEY, E. (2013). Options from life-cycle analysis for reducing greenhouse gas emissions from crop and livestock production systems. *International Journal of Agricultural Management* **2**, 70–80.
- WILKINSON, J. M., ALLEN, J. D., TUNNICLIFFE, R., SMITH, M. & GARNSWORTHY, P. C. (2014). Variation in composition of pre-grazed pasture herbage in the United Kingdom 2006–2012. *Animal Feed Science and Technology* **196**, 139–144.
- WILLIAMS, A. G., AUDSLEY, E. & SANDARS, D. L. (2006). *Determining the Environmental Burdens and Resource Use in the Production of Agricultural and Horticultural Commodities. Main Report*. Defra Research Project IS0205. Bedford, UK: Cranfield University. Available from: http://randd.defra.gov.uk/Document.aspx?Document=IS0205_3959_FRP.doc (verified 26 July 2016).
- YATES, C. M., CAMMELL, S. B., FRANCE, J. & BEEVER, D. E. (2000). Prediction of methane emissions from dairy cows using multiple regression analysis. In *Proceedings of the British Society of Animal Science 2000*, p. 94 (abstract). Penicuik, UK: British Society of Animal Science.

APPENDIX 1. Concentrations of dry matter, metabolizable energy, crude protein and neutral detergent fibre in forages and raw material feeds used in diet formulations and their carbon footprint

	DM (g/kg fresh weight)	ME (MJ/kg DM)	CP (g/kg DM)	ERDP (g/kg DM)	DUP (g/kg DM)	NDF (g/kg DM)	CFPfeed (g CO ₂ e/kg DM)	CFPlulc (g CO ₂ e/kg DM)	Total CFP (g CO ₂ e/kg DM)
Grazed grass	183	11.8	214	145	49	442	329	69	398*
Grass silage	250	10.1	135	102	27	412	304	78	382*
Maize silage	300	11.5	90	57	25	370	163	90	253
Wheat	876	13.6	130	91	33	89	424	165	589
Barley	860	13.2	141	114	22	154	406	188	594
Wheat straw	860	6.0	36	6	25	810	207	67	274
Sugarbeet pulp	890	12.5	107	54	43	320	330	0	330
Wheatfeed	860	12.0	180	124	48	395	271	87	359
Biscuit meal (waste)	900	12.3	130	54	23	180	139	0	139
Breakfast cereal (Weetabix waste)	950	14.8	124	52	62	70	140	0	140
Moist distillers grains (Vitagold)	350	14.5	360	287	26	389	45	0	45
Wheat dried distillers grains with solubles	920	13.7	348	223	74	290	786	11	797
Rapeseed meal	885	11.9	406	253	117	299	545	169	714
Soya bean meal	885	14.0	542	331	178	92	625	431	1056
Urea	950	0.0	2300	2156	129	0	3490	0	3490
Bypass fat	1000	38.0	0	0	0	0	1343	420	1763
Minerals & vitamins	990	0.0	0	0	0	0	2138	0	2138

From Thomas (2004), Vellinga *et al.* (2012), Premier Nutrition (2014) and Wilkinson *et al.* (2014).

* CFP values for grazed grass and grass silage calculated from the Cranfield systems based life-cycle analysis model (E. Audsley, personal communication) with additional emissions due to land use and land-use change from the Feedprint database (Vellinga *et al.* 2012).

APPENDIX 2. Equations used to calculate nitrogen excretion

The following equations were used to calculate MP requirements and supply. Those used without modification in the FiM system (Thomas 2004) were:

1. Dry matter intake (DMI, kg/d) = $-7.98 + 0.1033\text{FIP} - 0.00814(\text{FIP} \times \text{CDMI}) - 1.1185\text{CS} + 0.01896\text{W} + 0.7343\text{CDMI} - 0.00421(\text{CDMI})^2 + 0.04767\text{E}_l - 6.43(0.6916^{\text{WOL}}) + 0.007182[\text{FS}] + 0.001988([\text{CCP}] \times \text{CDMI})$

where FIP is forage intake potential (g/kg $\text{W}^{0.75}$); CDMI, concentrate DMI (kg/d); CS body condition score (1–5 scale); W live weight (kg) E_l , milk energy output (MJ/cow/d); WOL, week of lactation (constrained to maximum of 10) [FS], forage starch concentration (g/kg DM) and [CCP], crude protein concentration of the concentrate (g/kg total concentrate DM).

2. Effective rumen degradable protein (ERDP, g/d) = $[(0.9s_N/(0.9 + k_{liq})) + (b_{DN} c_N/(c_N + k_{liq})) + (b_N c_N/(c_N + k))]$ $\times \text{DMI} \times \text{CP}$

where s_N , b_{DN} , c_N and b_N are respectively the soluble, the degradable small particle, the fractional rate of degradation and degradable large particle N fractions of the feed; k_{liq} and k are respectively the fractional outflow rates of the liquid phase and the large N particles of the feed; CP is crude protein concentration of the feed (g/kg DM).

3. Microbial dry matter (MDM, g/d) = $(\text{ATP}_{\text{ssp}} \times Y_{\text{ANr,ssp}})$ $(\text{ATP}_{\text{lp}} \times Y_{\text{ATP lp}}) \times \text{DMI}$

where ATP_{ssp} and ATP_{lp} are supplies of ATP from the small and soluble particle (SSP) and the large particle (LP) fractions of the feed, respectively; $Y_{\text{ATP ssp}}$ and $Y_{\text{ATP lp}}$ are the efficiencies of MDM synthesis (g microbial DM/mol ATP) from the SSP and LP fractions respectively.

4. Microbial crude protein (MCP, g/d) = the lower of [ERDP] and [0.625MDM]
5. Microbial true protein (MTP, g/d) = 0.75MCP
6. Digestible microbial true protein (DMTP, g/d) = 0.85MTP
7. Undegradable dietary protein (UDP, g/d) = $0.9[(\text{DMI} \times \text{CP}) - \text{ERDP}]$

8. Digestible undegraded protein (DUP, g/d) = $\text{UDP} - (\text{DMI} \times 6.25\text{ADIN})$, where ADIN is acid-detergent insoluble N of the feed

9. Metabolizable protein supply (MP, g/d) = $\text{DMTP} + \text{DUP}$

10. Metabolizable protein requirement for Maintenance (MP_m , g/d) = $4.1\text{W}^{0.5} + 0.3\text{W}^{0.6} + 30\text{DMI} - 0.5((\text{DMTP}/0.8) - \text{DMTP}) + 2.34\text{DMI}$

11. Net protein requirement for milk (milkNP, g/d) = $0.95 \times \text{milk protein yield}$

12. Metabolizable protein requirement for Milk (milkMP, g/d) = $\text{milkNP}/0.68$

The following equations were derived for the formulations in this paper:

Urinary excretion

1. Endogenous urinary protein (EUP, g/d) = $4.1 \times \text{W}^{0.75}$

2. Surplus effective rumen degradable protein (ERDP_{excess}, g/d) = $\text{ERDP} - \text{MCP}$

3. Metabolic urinary protein (MUP, g/d) = $(\text{milkMP} - \text{milkNP})$

4. Microbial non-protein nitrogen (MNPN, g/d) = $0.25 \times \text{MCP}$

5. Endogenous urinary protein balance (EUP, g/d) = $2.34 \times \text{DMI}$

6. Milk non-protein nitrogen (NPN_{milk}, g/d) = $0.05 \times \text{milk protein yield}$

7. Total urinary N excretion (g/d) = $((\text{EUP} + \text{ERDP}_{\text{excess}} + \text{MUP} + \text{EUP})/6.25) + \text{MNPN} - \text{NPN}_{\text{milk}}$

Faecal excretion

1. Endogenous faecal protein (EFP, g/d) = $30 \times \text{DMI}$

2. Indigestible undegraded protein (iDUP, g/d) = $\text{DUP}/9$

3. Indigestible microbial true protein (iDMTP, g/d) = $0.75 \times \text{MCP}$

4. Endogenous protein absorbed from hind gut (EPHG, g/d) = $0.125 \times \text{DMTP}$

5. Total faecal N excretion (g/d) = $((\text{EFP} + \text{iDMTP} + \text{iDUP} - \text{EPHG})/6.25) + \text{ADIN}$